

Article

The Impact of Corridor Directional Configuration on Wayfinding Behavior during Fire Evacuation in Underground Spaces: An Empirical Study Based on Virtual Reality

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Abstract: This study employed Virtual Reality (VR) technology to investigate the influence of corridor directional configuration on evacuation wayfinding behavior in underground spaces. The study designed two virtual underground space fire evacuation scenarios with different forms of intersections, and recruited 115 volunteers to participate in the experiment. The results indicated that corridor directional configuration significantly affected participants' fire evacuation wayfinding behavior. At Y-shaped and T-shaped intersections with left and right turning options, participants showed a preference for choosing the right-side corridor. At L-shaped and T-shaped intersections with straight and turning options, participants tended to choose the straight path. Individual factors (such as gender, evacuation experience, and professional background) did not demonstrate significant effects on wayfinding choices in this study, though they may produce different evacuation outcomes in various scenarios. In practical evacuation design, corridor directional configuration should be organically integrated with other environmental factors to reinforce directional preferences and more effectively guide evacuation. The findings provide scientific evidence for underground space evacuation route design, which can be used to optimize evacuation signage and path configuration, thereby improving evacuation efficiency and safety. Future research could be conducted in more complex environments, considering additional variables to gain a more comprehensive understanding of evacuation behavior.

Keywords: fire evacuation in underground spaces; virtual reality; wayfinding behavior; corridor directional configuration; evacuation route choice



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1. Introduction

The rapid advancement of urbanization has led to a series of challenges, including land resource scarcity, environmental degradation, and traffic congestion. The development and utilization of underground spaces have become a crucial approach and significant strategic decision to address these urban issues [1]. Underground architectural structures, including subterranean transportation hubs, shopping centers, civil defense projects, and parking facilities, are increasingly prevalent. Compared to above-ground structures, underground spaces typically exhibit characteristics such as complex layouts, enclosed environments, limited redundant exits, intricate environmental information, and extended evacuation distances. In the event of emergencies like fires, these factors can impede personnel evacuation, potentially resulting in significant casualties and property losses [2]. Therefore, enhancing underground space safety management and improving emergency evacuation design are of paramount importance for safeguarding public life, property, and sustainable development in these environments.

Numerous factors influence the efficiency and safety of building evacuations, including disaster characteristics, the spatial environment, human behavior, and emergency management [3]. Among these, human behavior during the evacuation process is particularly crucial. As the primary agents of evacuation, individuals' behavior in disaster situations directly determines the efficiency and safety of the evacuation process [4]. Existing research indicates that human behavior in emergency scenarios differs significantly from normal conditions, including variations in speed, decision-making, following behavior, and self-organized group movement [5–8]. Consequently, a deeper understanding of the factors influencing human evacuation behavior in emergency situations and their underlying mechanisms is vital for optimizing building evacuation design, accurately assessing evacuation efficiency, and improving emergency management practices [9].

In evacuation behavior, wayfinding refers to the actions individuals take to choose evacuation routes based on environmental information and personal judgment. The accuracy of wayfinding is crucial for evacuation efficiency. This is especially important in underground spaces, where complex spatial layouts, poor lighting, and unclear environmental information pose significant challenges. Guiding individuals to select the optimal evacuation path and reduce evacuation time is a key issue for emergency safety in underground spaces [10]. Emo et al. argue that the wayfinding process during evacuation neither follows existing assumptions (such as following evacuation signs) nor is it a random process [11]. Instead, it adheres to a psychological cognitive model based on cue perception. Wayfinding decisions made by individuals in specific environments are influenced by both internal psychological factors (internal information) and external environmental factors (external information) [11,12]. Research by Penn et al. based on space syntax indicates that spatial configuration directly affects movement patterns among individuals [13], and Hillier et al. found a correlation between street network configuration and observed movement patterns [14]. Conroy categorizes external information influencing wayfinding during evacuation into explicit and implicit factors [11,15]. Explicit factors represent information that clearly directs individuals' evacuation route choices (such as signs, fire/smoke), while implicit factors are perceptible elements in the environment that may influence route choice (such as color, corridor width, landmarks, etc.).

In current evacuation spaces, evacuation signs are highly relied upon. However, evaluations of numerous fire incidents have revealed that many people do not choose the optimal exit as indicated by the evacuation signs, even if that path is free from smoke or fire [16,17]. A limited number of studies have explored the visual factors influencing evacuation wayfinding, such as natural lighting [18], the color and brightness characteristics of corridors [19,20], and the width or length of passageways [21]. When individuals make wayfinding decisions at multiple intersections, the directional information conveyed by the spatial layout itself (such as going straight, turning left, or turning right) may also influence their wayfinding behavior. Conroy, through analyzing the movement trajectories of individuals within buildings, found that people tend to go straight and avoid turning [15]. Related research indicates that there is a general right-side bias in directional choices [22]. Angelique et al. investigated and confirmed a preference for right turns in buildings, noting regional differences [23]. However, there is a lack of research on the impact of corridor directional configurations on wayfinding behavior during emergency evacuations, particularly empirical studies in underground environments. Given the complex layout of underground spaces, optimizing their design by effectively utilizing elements that influence wayfinding behavior is crucial for emergency safety in such environments.

Based on these considerations, this study proposes to employ Virtual Reality (VR) experimental methods, focusing on underground space environments, to investigate the influence of path direction on evacuation wayfinding during fire emergencies. VR technology has become a primary tool in environmental behavior research [24], especially in safety studies, due to its high immersion, internal validity, controllability, safety, and low cost [25–27]. It is considered an effective tool for studying evacuation behavior [26]. Through VR experiments, this study aims to answer the following questions: (1) Does the

directional information embedded in the corridor configuration of underground spaces influence wayfinding behavior during fire evacuations, and to what extent? (2) Is there a relationship between individual characteristics and wayfinding direction decisions? The results of this study are expected to deepen the understanding of the mechanisms influencing wayfinding behavior during fire evacuations in underground environments and provide evidence for optimizing evacuation safety design through rational use of spatial layouts.

2. Methodology

2.1. Experimental Platform

This study utilized a pre-established virtual reality (VR) platform for emergency evacuation behavior experiments developed by the research group [28] (Figure 1). The platform employs the Unreal Engine 4 to create the virtual environment, achieving high-immersion virtual interaction through the HTC Vive Pro Eye head-mounted display (HMD) and the Virtuix Omni omnidirectional treadmill. The platform incorporates an integrated data collection module capable of recording participants' positions and gaze directions within the virtual space at 0.5-s intervals in real-time. It also automatically generates data on evacuation trajectories and decision-making times. Previous human-computer interaction studies evaluating this platform have demonstrated its high level of environmental fidelity and natural human-computer interaction, indicating its effectiveness in simulating realistic emergency evacuation scenarios [18–29]. The platform specifications are presented in Table 1.

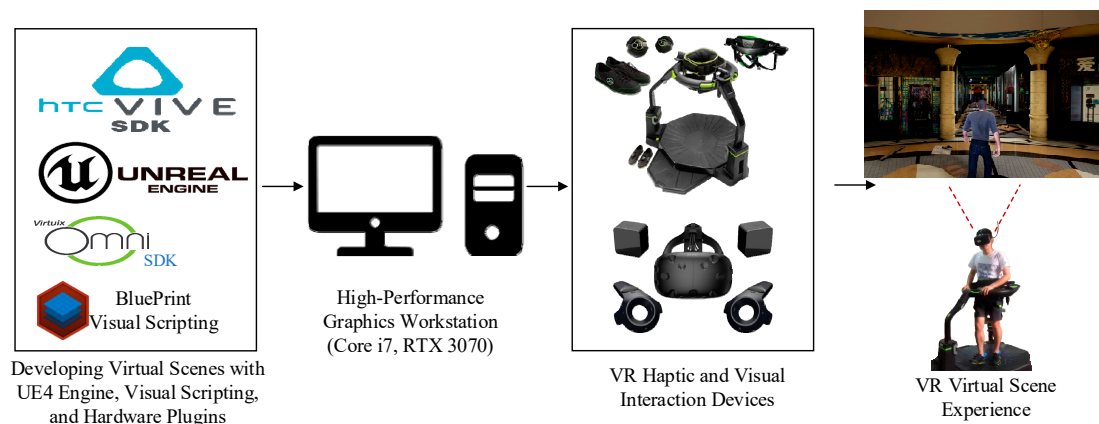


Figure 1. Configuration of the Virtual Display Experimental Platform.

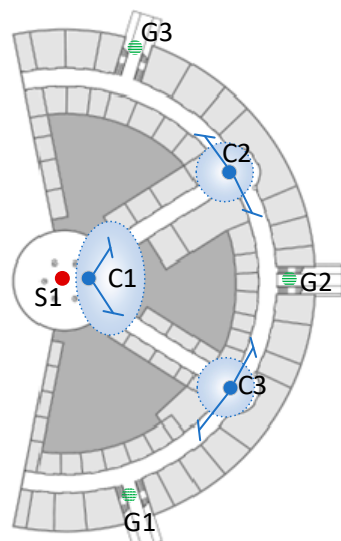
Table 1. Platform specifications and parameter information.

	Category	Type	Specifications
Hardware	Video and Audio Equipment	HTC Vive Pro Eye head-mounted display	Resolution: 3K (2880 × 1600), Refresh rate: 90 Hz, Field of view: 110°, Stereophonic audio
	Interaction Device	Virtuix Omni	Simulated locomotion capture, 360-degree rotation capability
	Computing Equipment	High-performance Graphics Workstation	Intel Core i9-11900K processor, NVIDIA GeForce RTX 3070 Ti graphics card, 32 GB RAM
Software	VR Engine	Unreal Engine 4.24	Open-source version with free licensing for research and educational purposes

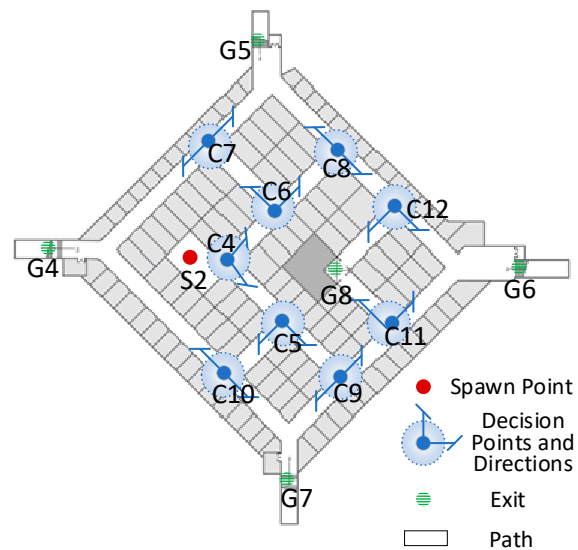
2.2. Experimental Scenario Design

This experiment focuses on directional choice behavior during evacuation in underground spaces. Two virtual evacuation scenarios with different types of intersections were designed based on the typical grid-like layout of underground spaces. As shown in

Figure 2c,e, Scenario 1 was modeled after the actual layout of the Jinyuan Nightless City underground shopping mall in Chongqing, with corridors 3 m wide and 3.3 m high. As illustrated in Figure 2d,f, Scenario 2 was an abstract underground space scenario composed of various T-shaped intersections, based on the Sanxia Square underground shopping mall in Chongqing, with corridors 2.4 m wide and 3 m high. Signage systems were removed from the scenarios, and corridor characteristics were similar within each scenario. The virtual scenarios also recreated the atmosphere of underground commercial spaces based on preliminary research. The simulated underground space evacuation only had dim emergency lighting conditions, with no significant differences in lighting or color between corridors at each intersection. During the experiment, background audio indicated an ongoing fire in the mall.



(a) Scene 1 Layout and Setup



(b) Scene 2 Layout and Setup



(c) Scene 1 Real-time Rendering Screenshot
(View from S1 to C1)



(d) Scene 2 Real-time Rendering Screenshot
(View from C4 to C6)



(e) Scene 1: Model based on Chongqing
Jinyuan Night City Underground mall



(f) Scene 2: Model based on the underground
mall of Chongqing Three Gorges Square

Figure 2. Scenario layout and realistic renderings.

Participants for the two scenarios were independent, and it was assumed that each decision made by participants was an independent event. The layout of Scenario 1 is shown in Figure 2a. In this scenario, participants start from point S1 and must make decisions at a minimum of two path intersections before reaching the final exit. The first decision point, C1, is a Y-shaped intersection requiring a left or right choice. The second decision points (C2 and C3) are T-shaped intersections also requiring left or right choices. Apart from direction, visual information at all decision points is consistent. Participants ultimately leave the scene through any of the exits G1~G3. The layout of Scenario 2 is shown in Figure 2b. In this scenario, participants start from a store at point S2 and must pass through at least three intersection decision points before reaching any of the exits G4~G8. After leaving the store, they immediately face a Y-shaped intersection (C4) requiring a left or right choice, followed by several $\vdash$, $\dashv$, or T-shaped intersections before reaching an exit. In Scenario 2, there are no visual differences between the corridors. To ensure that the visual information at the end of corridors does not influence current choices, lighting is adjusted during the evacuation process to simulate the emergency lighting conditions of an underground space evacuation. The evacuation scene is relatively dark, and at decision intersections, only the visual information of the currently connected corridors is visible.

In both scenarios, all intersection navigation involves binary comparisons of forward, left, and right options. Disregarding repeated path-finding, the preset direction types for all intersections are listed in Table 2. For visual representations of the various intersection types, see Supplementary Figures S1–S6.

Table 2. Decision point information of various intersection types.

Intersection Type	Preset Decision Points
Y	C1, C4
T	C2, C3, C7, C8, C9, C10, C11
$\vdash$	C5, C12
$\dashv$	C6, C11

2.3. Participants and Experimental Procedure

A total of 115 volunteer participants were recruited through posters and social media networks, primarily consisting of university students. The sample comprised 72 participants (37 males, 35 females) in Scenario 1, aged between 15 and 35 years, and 43 participants (25 males, 18 females) in Scenario 2, aged between 17 and 60 years, as shown in Table 3. Prior to the experiment, all participants completed a questionnaire to collect demographic information, confirm their choices within the scenarios, and evaluate the VR experimental system. Upon completion of the experiment, each participant received the CNY 20 compensation.

Table 3. Demographic characteristics of experimental participants.

Scenario	Samples	Gender		Age (Years)			Evacuation Experience		Professional Background	
		M	F	R	Mean	SD	Y	N	Engineering Majors	Liberal Arts Majors
Scenario 1	72	37	35	15–35	24	2.768	37	35	46	26
Scenario 2	43	25	18	17–60	22	8.571	24	19	26	17

Prior to the commencement of the experiment, participants were informed of their right to withdraw at any time. Both experiments informed participants in the pre-experiment questionnaire that the content was related to fire evacuation. The main experimental procedure is as follows, as illustrated in Figure 3a:

- Completion of a pre-experiment questionnaire. This primarily collected participants' demographic information, including gender, age, academic background, educational level, fire evacuation experience, fire incident history, and prior VR experience.
- Experimental training. Before the formal test scenario, participants first explored a maze environment, as shown in Figure 3b. This was designed to familiarize participants with the VR system operation, enabling them to adapt to the virtual environment and interactive locomotion methods. The typical completion time for the maze scenario ranged from 0.5 to 2 min.
- Formal testing. Figure 3c depicts a participant during the experiment. A time limit of 10 min was set for each formal scenario. Participants were allowed to terminate the experiment prematurely if they experienced any discomfort. If a participant failed to reach the exit within the specified time, it was considered an evacuation failure. The study utilized data only from participants who successfully completed the evacuation experiment.
- Upon completion of the formal experiment, staff members assisted participants in removing the experimental equipment, after which participants received their compensation.

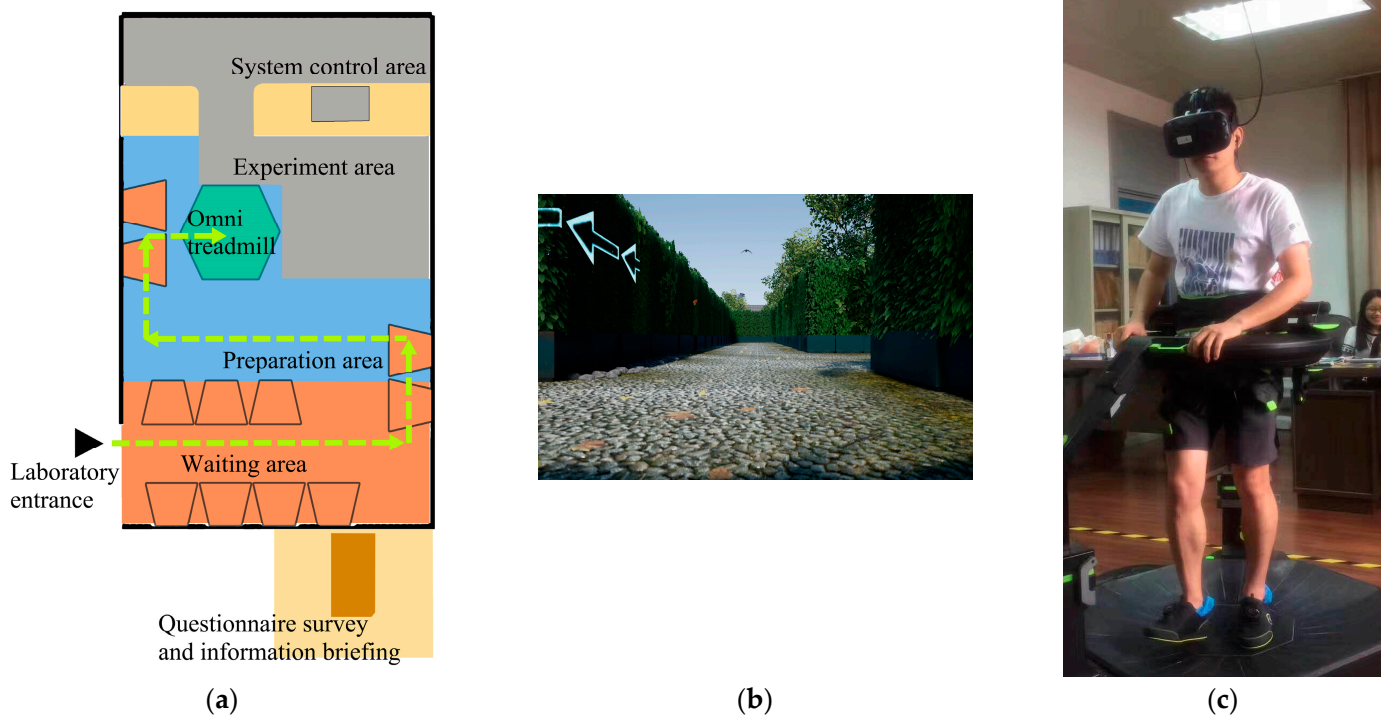


Figure 3. Experimental setup. (a) Schematic diagram of experimental area zoning and flow lines; (b) screenshot of the maze scenario; (c) participant during the experiment process.

2.4. Data Recording and Analysis

Participant movements in VR were automatically recorded using UE4 C++ scripts. Coordinates were recorded every 0.5 s, with each sample data stored separately. Python scripts were used to track each participant's movement trajectory to determine their wayfinding decisions. Before and after the experiment, questionnaire data was self-input by participants and collected in Excel files. Data analysis primarily employed descriptive statistics and hypothesis testing methods. Statistical analyses were conducted using Excel (2016), SPSS (version 27), GraphPad Prism 9.5, and Python (3.7). The significance level was set at 0.05.

3. Results

3.1. Impact of Corridor Direction Configuration on Evacuation Wayfinding

3.1.1. Left-Right Turn Choices: Y-Shaped and T-Shaped Intersections

Figure 4a,b presents the superimposed evacuation trajectories of all participants in Scenarios 1 and 2, respectively. These trajectory overlays provide a visual representation of participants' choices. At Y-shaped intersections, the difference in left-right selection trajectories was not particularly pronounced. However, at T-shaped intersections, the distinction was more apparent, with some participants also exploring potential alternative exits or corridors from the starting position. Examining individual behaviors based on the trajectory overlays in Figure 4, participants who initially chose the right path showed a notably higher trajectory density on the right side during their second path selection. In contrast, those who initially chose the left path demonstrated a more balanced distribution between left and right corridors in their second selection. This suggests that for specific individuals, the left-right path selection during evacuation wayfinding is not random but rather influenced by individual preferences.

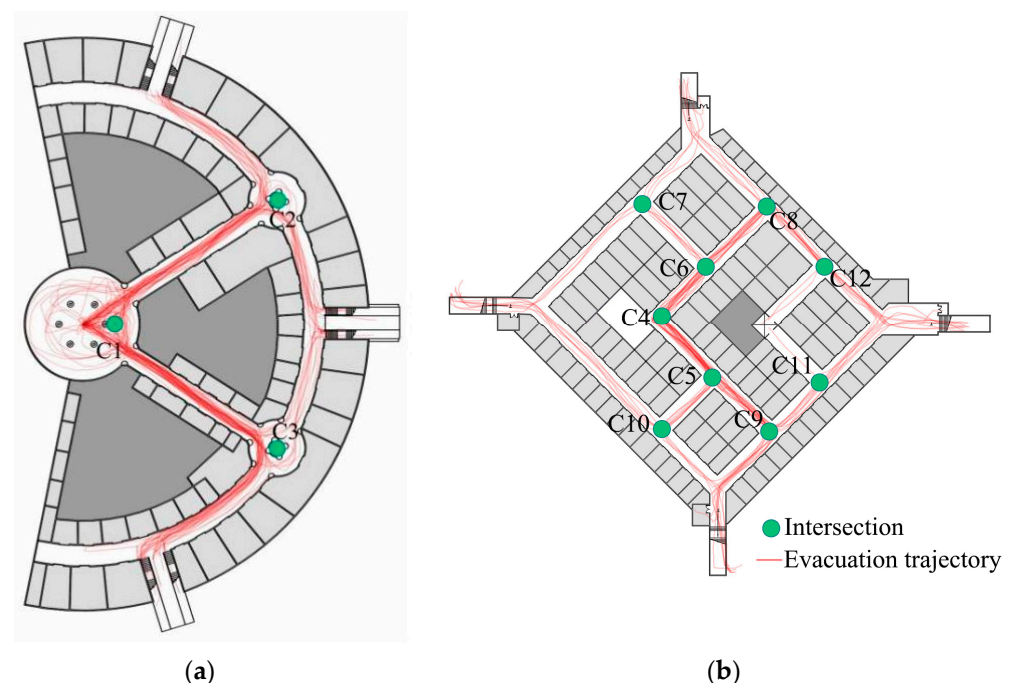


Figure 4. (a) Superimposed evacuation trajectory map of participants in Scenario 1; (b) Superimposed evacuation trajectory map of participants in Scenario 2.

Chi-square tests were conducted on pedestrians' directional choices at four types of intersections (Table 4). Chi-square homogeneity tests were performed on each directional choice at the "Y-shaped" intersections C1 and C4 to verify whether participants' route selection preferences were influenced by corridor directional configurations. Table 4 shows that at Y-shaped intersections, 58.3% of participants chose the right corridor, while 41.7% chose the left corridor. At T-shaped intersections, 61.7% of participants chose the right corridor, and 38.3% chose the left corridor. Table 4 displays the percentages of directional choices and chi-square test results of corresponding intersections in the experiment. The chi-square test results indicate significant differences in directional choices at "Y-shaped" intersections ($p < 0.001$), suggesting that the probability of participants choosing the right corridor is significantly higher than choosing the left corridor in their route selection preferences. Similarly, chi-square homogeneity tests were conducted on each directional choice at "T-shaped" intersections C2, C3, C7, C8, C9, and C10 to analyze participants' directional choices and determine whether they were influenced by corridor directional configurations. The chi-square test results showed significant differences in directional choices ($p < 0.001$). Table 5

presents the statistical analysis and differential analysis of decision-making for each type of intersection. The results indicate that there were no significant differences in wayfinding decisions among intersections of the same type. At Y-shaped and T-shaped intersections, participants demonstrated a greater tendency to choose the right-hand corridor.

Table 4. Chi-square test results of direction choices at Y-shaped and T-shaped intersections.

Intersection Type	Direction Choice Samples (Percentage)		Chi-Square
	Left	Right	
Y	48 (41.7%)	67 (58.3%)	$\chi^2 = 110.925; p < 0.001; N = 115$
T	44 (38.3%)	71 (61.7%)	$\chi^2 = 110.806; p < 0.001; N = 115$

Table 5. Results of directional choices for each of the 12 corridors.

Intersection Type	Corridor	Direction Choice Samples (Percentage)			Chi-Square (Within-Type)
		Left	Right	Front	
Y	C1	30 (41.7%)	42 (58.3%)	—	$\chi^2 = 0.012; p = 0.984; N = 115$
	C4	18 (41.9%)	25 (58.1%)	—	
T	C2	14 (46.7%)	16 (53.3%)	—	$\chi^2 = 2.384; p = 0.794; N = 115$
	C3	13 (31%)	29 (69%)	—	
	C7	3 (50%)	3 (50%)	—	
	C8	4 (33.3%)	8 (66.7%)	—	
	C9	7 (41.2%)	10 (58.8%)	—	
	C10	3 (37.5%)	5 (62.5%)	—	
┌	C5	—	8 (32%)	17 (68%)	$\chi^2 = 0.141; p = 0.708; N = 33$
	C12	—	2 (25%)	6 (75%)	
└	C6	6 (33.3%)	—	12 (66.7%)	$\chi^2 = 0.907; p = 0.341; N = 25$
	C11	1 (14.3%)	—	6 (85.7%)	

3.1.2. Straight and Turn Choices: ┌-Shaped and └-Shaped Intersections

The superimposed trajectory maps (Figure 4) provide a clear visual representation of the notable differences in participants' path direction choices at ┌-shaped and └-shaped intersections. The trajectory density in straight corridors was consistently higher than that in turning corridors, suggesting that specific individuals exhibit distinct preferences for straight paths over turns during evacuation wayfinding.

Chi-square tests were conducted on the directional choice results at “┌-shaped” intersections to assess homogeneity (Table 6) and determine whether direction selection was influenced by corridor configuration. At ┌-shaped intersections, 69.7% of participants opted for the straight corridor, while 30.3% chose the right corridor. Similarly, at └-shaped intersections, 72% of participants selected the straight corridor, with 28% choosing the left corridor. The proportion of participants choosing the straight corridor at both ┌-shaped and └-shaped intersections was approximately 70%, indicating an asymmetry in path selection during overall crowd evacuation, with a significantly higher preference for straight paths compared to left or right turns. Synthesizing the participants' path direction choice results, it can be concluded that participants demonstrated a stronger inclination towards selecting the straight corridor at both ┌-shaped and └-shaped intersections.

Table 6. Chi-square test results of direction choices at ┌-shaped and └-shaped intersections.

Intersection Type	Direction Choice Samples (Percentage)			Chi-Square
	Left	Right	Front	
┌	—	23 (69.7%)	10 (30.3%)	$\chi^2 = 28.435; p < 0.001; N = 33$
└	18 (72%)	—	7 (28%)	$\chi^2 = 20.286; p < 0.001; N = 25$

Figure 5 presents a stacked percentage bar chart of the chi-square test results of participants' directional choices at four different intersection types, clearly illustrating that participants exhibit distinct directional preferences. This observation aligns with the findings from the trajectory maps. At Y-shaped and T-shaped intersections, participants demonstrate a preference for the right corridor, while at T-shaped and + -shaped intersections, they tend to favor the straight corridor.

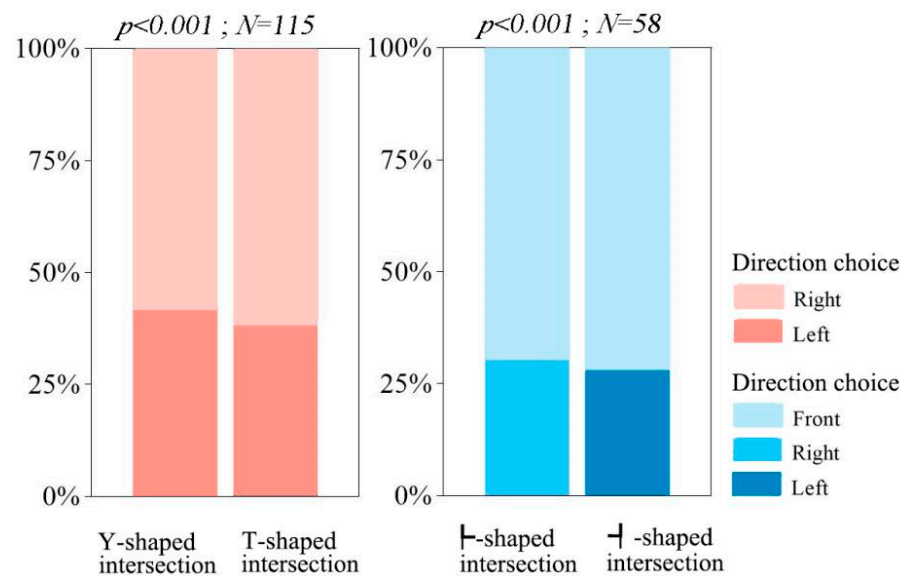


Figure 5. Stacked percentage bar chart of directional choices at Y-shaped, T-shaped, T-shaped, and + -shaped intersections.

3.2. Individual Factors of Subjects

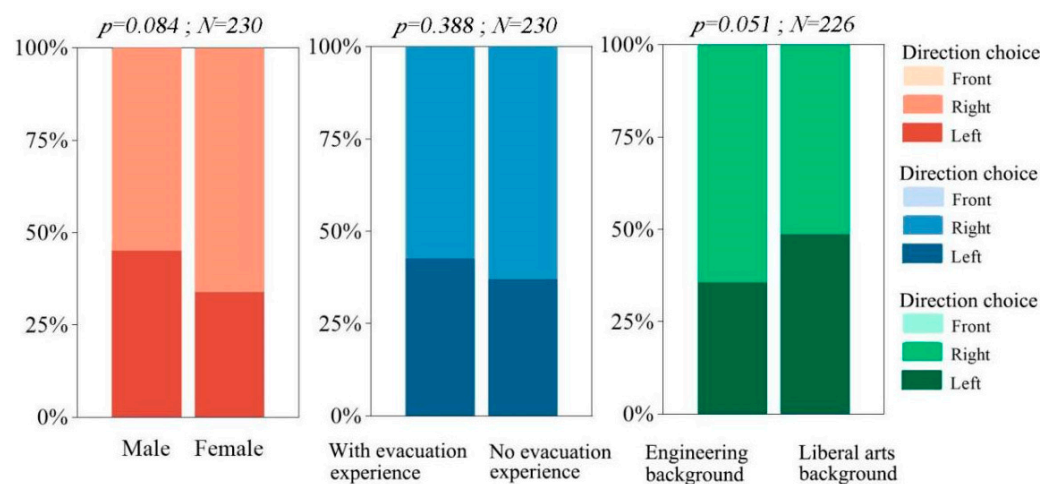
Existing research has identified several individual factors that influence evacuation behavior, including gender, age, perceptual abilities, judgment, knowledge and experience, mobility status, body mass index, culture, geographical region, and ethnicity [30,31]. In this study, we also collected data on some individual factors and analyzed the correlation between these factors and pedestrians' directional choices at different types of intersections. The individual factors considered in this analysis include gender, evacuation experience, and professional background.

3.2.1. Y-Shaped and T-Shaped Intersections

Table 7 presents the results of chi-square tests of directional choices at Y-shaped and T-shaped intersections. The chi-square test results indicate that there are no statistically significant differences in participants' wayfinding behavior during evacuation based on gender ($p > 0.05$), evacuation experience ($p > 0.05$), or professional background ($p > 0.05$). Figure 6, which displays the percentage stacked chart of the chi-square test results, visually demonstrates that the influence of individual factors on participants' directional choices at Y-shaped and T-shaped intersections is not prominent. Table 8 presents a logistic regression analysis of the individual factors of subjects and their direction selection results at Y-shaped and T-shaped intersections. The results are consistent with the single-factor chi-square test, indicating that the influence of these factors did not reach statistical significance in this study. There were no statistically significant differences in direction selection based on individual pedestrian factors at Y-shaped and T-shaped intersections. However, descriptive statistics suggest that participants with different professional backgrounds may exhibit varied performances when making directional choices during evacuation wayfinding.

Table 7. Chi-square test results of the impact of individual factors on wayfinding direction choice at Y-shaped and T-shaped intersections.

Individual Factors		Direction Choice Samples (Percentage)		Chi-Square
		Left	Right	
Gender	Male	56 (45.2%)	68 (52.8%)	$\chi^2 = 2.986; p = 0.084; N = 230$
	Female	36 (34%)	70 (66%)	
Evacuation experience	Yes	52 (42.6%)	70 (57.4%)	$\chi^2 = 0.745; p = 0.388; N = 230$
	No	40 (37%)	68 (63%)	
Academic background	Engineering	50 (35.7%)	90 (64.3%)	$\chi^2 = 3.801; p = 0.051; N = 226$
	Liberal arts	42 (48.8%)	44 (51.2%)	

**Figure 6.** Stacked percentage bar chart of chi-square test results of direction choice influenced by individual factors at Y-shaped and T-shaped intersections.**Table 8.** Logistic regression analysis results of individual factors and wayfinding directional choices at Y-shaped and T-shaped intersections.

Variable		The Direction Choice of Subjects at Y-Shaped and T-Shaped Intersections		
		OR	95%CI	p
Gender	Male	Ref.		
	Female	0.423	0.133~1.343	0.144
Evacuation experience	Yes	Ref.		
	No	0.632	0.202~1.979	0.430
Academic background	Engineering	Ref.		
	Liberal arts	2.339	0.755~7.251	0.141

3.2.2. T-Shaped and ⊥-Shaped Intersections

Due to the limited sample size of wayfinding decisions at T-shaped and ⊥-shaped intersections during the evacuation process, this study opted to combine left and right turn direction choice data into a single “turning” category for analysis alongside straight-ahead data. Table 9 presents the results of chi-square tests conducted on direction choices at T-shaped and ⊥-shaped intersections. The chi-square test results indicate that participants’ gender ($p > 0.05$), evacuation experience ($p > 0.05$), and professional background ($p > 0.05$) do not exhibit statistically significant differences in direction choice during evacuation wayfinding behavior. Figure 7, a percentage stacked bar chart of the chi-square test results, provides a clear visual representation demonstrating that individual factors have no apparent influence on participants’ direction choices at T-shaped and ⊥-shaped intersections. Table 10 presents the results of logistic regression analysis examining the

relationship between subjects' individual factors and direction choices at T-shaped and Y-shaped intersections. The findings reveal that the impact of these factors did not reach statistical significance, indicating no statistically significant differences in direction choices attributable to pedestrians' individual factors at T-shaped and Y-shaped intersections.

Table 9. Chi-square test results of the influence of individual factors on wayfinding direction choice at T-shaped and Y-shaped intersections.

Individual Factors		Direction Choice Samples (Percentage)		Chi-Square
		Turn	Front	
Gender	Male	8 (20.5%)	31 (79.5%)	$\chi^2 = 1.873$; $p = 0.171$; $N = 64$
	Female	9 (36%)	16 (64%)	
Evacuation experience	Yes	10 (30.3%)	23 (69.7%)	$\chi^2 = 0.036$; $p = 0.849$; $N = 58$
	No	7 (28%)	18 (72%)	
Academic background	Engineering	10 (28.6%)	25 (71.4%)	$\chi^2 = 0.023$; $p = 0.879$; $N = 58$
	Liberal arts	7 (30.4%)	16 (69.6%)	

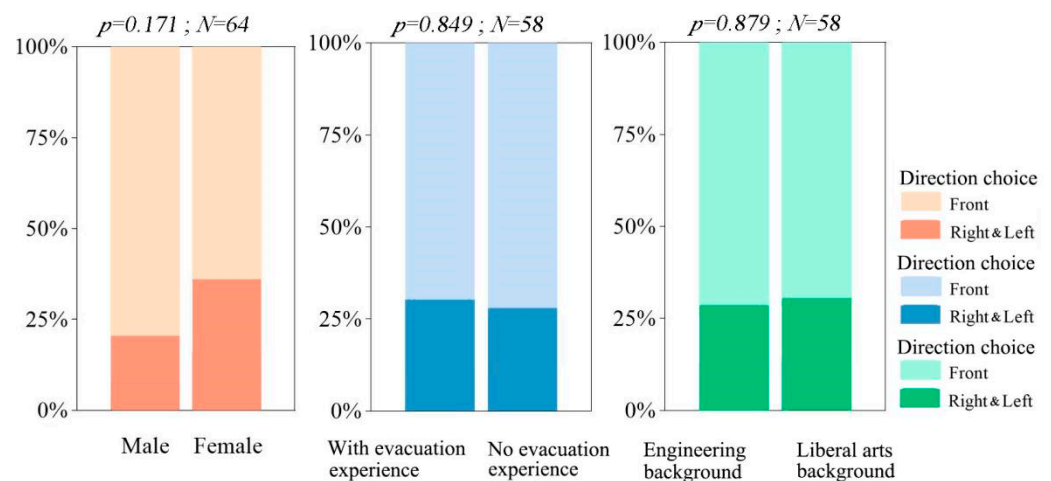


Figure 7. Stacked percentage bar chart of chi-square test results of direction choice influenced by individual factors at T-shaped and Y-shaped intersections.

Table 10. Logistic regression analysis results of individual factors and wayfinding directional choices at T-shaped and Y-shaped intersections.

Variable		The Direction Choice of Subjects at Y-Shaped and T-Shaped Intersections		
		OR	95%CI	p
Gender	Male	Ref.		
	Female	0.629	0.155~2.561	0.518
Evacuation experience	Yes	Ref.		
	No	0.781	0.198~3.078	0.724
Academic background	Engineering	Ref.		
	Liberal arts	0.881	0.214~3.633	0.861

4. Discussion

4.1. Corridor Direction Configuration and Evacuation Wayfinding Behavior

This study aims to investigate the impact of corridor directional configurations on wayfinding behavior during emergency evacuations, with the objective of informing safety design and policy formulation of underground spaces. In the absence of other influencing factors, this issue was explored through statistical analysis of pedestrian performance at various intersection types and participants' wayfinding behaviors. The research employed

Virtual Reality (VR) experiments to examine the influence of corridor directional configurations on wayfinding behavior during underground space evacuations. The results indicate that corridor directional configurations significantly affect participants' evacuation choice behavior. At Y-shaped and T-shaped intersections, based on left and right turn options, participants demonstrated a preference for right-side corridors. This finding aligns with previous research [22,23], suggesting the existence of directional preferences during emergency evacuations. Such preferences may be associated with human cognitive and behavioral characteristics, including the prevalence of right-handedness, right-side visual priority, and cultural habits. At $\perp$ -shaped and $\dashv$ -shaped intersections, participants exhibited a tendency to choose straight paths. This preference may be attributed to the lower cognitive load of straight paths, reduced physical and cognitive effort required to maintain the current direction of movement, and the typically broader visual field provided by straight corridors. Dalton's research indicates that individuals indeed have angular preferences in path selection, favoring routes with fewer turns [32]. Similarly, Hölscher found that people tend to move as directly as possible towards visible horizontal path directions during wayfinding [33], which corroborates our observed "straight-line preference" phenomenon. Based on these findings, designers can optimize fire evacuation safety in underground spaces by leveraging these directional choice preferences. The design of evacuation guidance signs, corridor widths, and lighting at underground intersections should be integrated with pedestrians' directional preferences to configure corridor directions. Efforts should be made to guide pedestrians to turn right or proceed straight ahead, which would significantly enhance fire evacuation effectiveness in underground spaces and facilitate improved evacuation layouts.

Conroy categorized external information influencing evacuation wayfinding into explicit and implicit factors [11,15]. Explicit factors include information that clearly indicates evacuation direction choices, such as signage, while implicit factors encompass perceptible elements in the environmental configuration (e.g., passage width, brightness) that may influence direction selection. When individuals make wayfinding decisions at multiple intersections, the directional configuration information (such as straight ahead, left turn, or right turn) conveyed by the spatial layout itself may also influence evacuation decisions based on external information at intersections (guidance signs, passage width, and brightness). Currently, there is no specific research on the impact of passage directional configuration on evacuation decisions. Only a few studies have included the influence of environmental factors' directional configuration on wayfinding direction choices (Table 11), finding that the directional configurations of evacuation signs, path width, and brightness all affect direction selection to some extent. Vilar et al.'s research indicates that guidance signs have a significant impact on directional decisions during evacuation, but the directional setup of guidance signs does not notably affect their guiding function [20]. Regarding path width, Vilar et al.'s studies show that participants tend to choose wider passages, with significant differences in the influence of directional configuration on left and right sides. The tendency to turn right is more pronounced when configured on the right side compared to turning left when configured on the left side. Concerning path brightness, Vilar et al. found that participants prefer brighter passages, with an equal tendency to choose the side with configured brightness regardless of left or right placement [11]. Vilar et al. also discovered that passage brightness has a more significant impact on wayfinding decisions than passage width [20]. These findings highlight the importance of passage directional configuration in evacuation decisions and indicate the need to consider the interaction of multiple environmental factors when designing evacuation routes. Our experimental setup excluded the influence of signage systems, width, and brightness, focusing on the impact of passage directional configuration on direction choice. This aspect has not been extensively explored in many existing studies, thus filling a gap in current research to some extent. In future studies on factors affecting evacuation wayfinding, directional configuration should be considered as a fundamental type of information, and its influence on other wayfinding factors should be examined. As observed from the aforementioned

studies, this influence is not a simple linear enhancement or reduction. Existing research suggests that it may have no effect in the presence of certain dominant factors, while it may have an impact in the presence of others. In practical applications and research, the synergistic effects of multiple wayfinding influencing factors in real environments should be considered to provide more effective evacuation guidance. Based on the results of this study, designers can utilize this directional choice preference to optimize fire evacuation safety in underground spaces. Combining the design of evacuation guidance signs, passage width, and lighting at underground space intersections with pedestrians' directional choice preferences for passage directional configuration, and guiding pedestrians to turn right and go straight as much as possible, will greatly promote fire evacuation in underground spaces and better arrange the evacuation layout of underground spaces.

Table 11. Related studies on the impact of directional configurations of environmental factors on wayfinding decisions.

Environmental Influencing Factors	Directional Settings	Directional Choice Differences	Ref.
Evacuation signage	No	The directional configuration of guiding signs did not have a significant impact on direction choice.	Xie and Filippidis et al., 2012 [34]
	No		Vilar and Rebelo et al., 2013 [11]
	No		Tang and Wu et al., 2009 [35]
	Yes		Vilar and Rebelo et al., 2014 [20]
	No		Vilar and Rebelo et al., 2015 [19]
Path width	No	The directional configuration of corridor width on the left and right sides showed significant differences in its effect on directional choice, with the tendency to turn right when configured on the right side being more pronounced than the tendency to turn left when configured on the left side.	Vilar and Rebelo et al., 2013 [11]
	No		Snopková and De Cock et al., 2023 [21]
	Yes		Vilar and Rebelo et al., 2014 [20]
Path brightness	Yes	Regardless of whether the directional configuration of corridor brightness was on the left or right side, participants showed an equal tendency to choose the side in which the corridor brightness was configured.	Vilar and Rebelo et al., 2013 [11]
	No	Regardless of whether the directional configuration of corridor brightness was on the left or right side, participants showed an equal tendency to choose the side in which the corridor brightness was configured. The directional configuration of corridor brightness had a more significant impact on wayfinding decisions compared to the directional configuration of corridor width.	Nilsson and Frantzich et al., 2005 [36]
	Yes		Vilar and Rebelo et al., 2014 [20]
	No		Wang and Liang et al., 2022 [18]

4.2. Individual Factors of Subjects and Evacuation Wayfinding Behavior

At the outset of this study, we considered the rarity of left-handedness in China, where the proportion of left-handed individuals is significantly lower than in Western countries. This disparity is influenced by regional cultural differences, with many left-handed individuals being corrected to use their right hand by parents during childhood [37,38]. In our participant demographic analysis, we found that left-handed individuals comprised less than 5% of the sample, which was insufficient for statistical analysis. Consequently, this study did not investigate left-handedness as an individual factor. Chi-square tests and logistic regression analyses indicated that individual factors (such as gender, evacuation experience, and professional background) did not significantly influence wayfinding choices. However, this does not imply that these factors are universally inconsequential. The results of this study may be limited by the sample population, experimental environment, and statistical methods employed. In different emergency scenarios, individual factors may exert varying influences on behavioral decision-making. For instance, gender differences

might become more pronounced in more complex or high-stress environments [39,40]. Moreover, experience gained from safety training and evacuation drills may play a crucial role in enhancing evacuation efficiency and decision-making accuracy. Therefore, future research should further explore the influence of these factors across various scenarios and environments.

4.3. Limitations and Future Prospects

This study has several limitations, summarized as follows:

1. While this study employed VR technology to simulate underground space evacuation environments and validated its effectiveness in studying personnel evacuation behavior, there remains a gap between VR simulations and real emergency evacuation scenarios. Participants' psychological and physiological responses in virtual environments may differ from those in real environments. Simultaneously, VR technology provides a highly immersive experimental environment, allowing participants to conduct evacuation drills under safe, controlled conditions while precisely recording behavioral data. Future experiments using VR systems that can more realistically simulate complex perceptions and emotional responses in emergency situations could further enhance the authenticity of the experimental environment, offering new methods and tools for future evacuation behavior research with broad application prospects.
2. The participants in this study were primarily university students, potentially exhibiting similarities in age, educational background, physical fitness, and psychological state. The individual-based experiments did not account for the influence of group behavior and may not comprehensively represent the general population. Additionally, the sample size for intersections involving turns and straight paths was limited. Individuals from different age groups, cultural backgrounds, and physical conditions may exhibit varying behaviors during emergency evacuations. For instance, the prevalence of left-handedness varies across different countries. Consequently, the generalizability of the research findings may be constrained. Future studies are recommended to recruit a more diverse pool of participants, encompassing individuals from various age groups, cultural backgrounds, and physical conditions, to enhance the universality of research outcomes.
3. VR experiments are typically conducted in a short time and limited spatial environment, and are unable to fully simulate long-term, large-scale, multi-factor evacuation processes. In real emergency evacuations, participants may need to navigate complex environments for extended periods, influenced by multiple factors such as the sequence of decision points and smoke propagation. Behavioral patterns in such scenarios are more intricate and cannot be adequately represented by simple linear combinations. Future research should aim to design evacuation simulation experiments that are long-term, large-scale, and multi-factorial. These studies should investigate participants' behavioral patterns during prolonged evacuation processes, simulate multi-stage evacuation scenarios under the combined influence of various factors, and examine evacuations.

5. Conclusions

Through virtual reality experiments, this study found that corridor direction configuration in underground spaces significantly influences personnel evacuation wayfinding behavior:

1. Participants exhibited a higher proportion of choosing the right-side path at T-shaped and Y-shaped intersections with left and right turns, indicating a certain individual preference in path selection during evacuation wayfinding.
2. At T-shaped and Y-shaped intersections with straight and turning options, there was a higher proportion of individuals choosing the straight path. This asymmetry in path selection between straight and turning directions during crowd evacuation demonstrates a strong directional preference.

3. Individual factors (gender, evacuation experience, professional background) did not show significant influences on personnel evacuation wayfinding behavior in this study. However, participants with different professional backgrounds may perform differently when making evacuation wayfinding direction choices, potentially resulting in different evacuation effects in various scenarios.

This study suggests that the design of evacuation guiding signs, corridor width, and lighting at underground space intersections should be combined with pedestrians' directional selection preferences for corridor directional configuration, aiming to guide pedestrians to turn right and go straight. Simultaneously, more intuitive and continuous straight paths should be designed, guiding people onto optimal routes from the initial stages of evacuation, while considering additional visual cues or guiding signs at left turns. Considering these environmental factors comprehensively, we recommend organically integrating corridor directional configuration with other environmental factors in practical evacuation design. More prominent signs should be placed on right-turning and straight corridors, increasing their width and brightness levels to reinforce people's directional preferences, thereby more effectively guiding evacuation. Furthermore, further research on the influence of individual factors in different scenarios can provide a basis for developing more comprehensive and effective evacuation strategies. This study fills the research gap regarding the impact of corridor configuration on individual wayfinding decisions, offering scientific evidence for underground space evacuation path design, optimizing evacuation signage and path settings, and improving evacuation efficiency and safety.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/fire7080294/s1>, Figure S1: Screenshot of T-Shaped Intersection in Scene 1; Figure S2: Screenshot of Y-Shaped Intersection in Scene 1; Figure S3: Screenshot of Y-Shaped Intersection in Scene 2; Figure S4: Screenshot of T-Shaped Intersection in Scene 2; Figure S5: Screenshot of T-Shaped Intersection in Scene 2; Figure S6: Screenshot of T-Shaped Intersection in Scene 2.

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References

1. 2023 Blue Book on China's Urban Underground Space Development; Strategic Consulting Center of Chinese Academy of Engineering, Underground Space Branch of Chinese Society for Rock Mechanics and Engineering, Urban Planning Society of China: Beijing, China, 2024.
2. Wang, D.; Zhou, T.; Zhang, H.; Shi, L. Evacuation organization strategy for deep underground space based on sub-safe areas. *New Archit.* **2021**, 47–52.
3. Kobes, M.; Helsloot, I.; De Vries, B.; Post, J.G. Building safety and human behaviour in fire: A literature review. *Fire Saf. J.* **2010**, 45, 1–11. [[CrossRef](#)]

4. Ronchi, E.; Nilsson, D. Fire evacuation in high-rise buildings: A review of human behaviour and modelling research. *Fire Sci. Rev.* **2013**, *2*, 7. [[CrossRef](#)]
5. Fahy, R.; Proulx, G. Toward creating a database on delay times to start evacuation and walking speeds for use in evacuation modeling. In Proceedings of the 2nd International Symposium on Human Behaviour in Fire, Boston, MA, USA, 26–28 March 2001; pp. 175–183.
6. Bode, N.W.; Holl, S.; Mehner, W.; Seyfried, A. Disentangling the Impact of Social Groups on Response Times and Movement Dynamics in Evacuations. *PLoS ONE* **2015**, *10*, e0121227. [[CrossRef](#)] [[PubMed](#)]
7. Nilsson, D.; Johansson, M.; Frantzich, H. Evacuation experiment in a road tunnel: A study of human behaviour and technical installations. *Fire Saf. J.* **2009**, *44*, 458–468. [[CrossRef](#)]
8. Ronchi, E.; Gwynne, S.M.; Purser, D.A.; Colonna, P. Representation of the Impact of Smoke on Agent Walking Speeds in Evacuation Models. *Fire Technol.* **2013**, *49*, 411–431. [[CrossRef](#)]
9. Haghani, M. Optimising crowd evacuations: Mathematical, architectural and behavioural approaches. *Saf. Sci.* **2020**, *128*, 104745. [[CrossRef](#)]
10. Wang, D.; Yang, Y.; Zhou, T.; Yang, F. An investigation of fire evacuation performance in irregular underground commercial building affected by multiple parameters. *J. Build. Eng.* **2021**, *37*, 102146. [[CrossRef](#)]
11. Vilar, E.; Rebelo, F.; Noriega, P.; Teles, J.; Mayhorn, C. The influence of environmental features on route selection in an emergency situation. *Appl. Ergon.* **2013**, *44*, 618–627.
12. Arthur, P.L.; Passini, R. *Wayfinding: People, Signs, and Architecture*; McGraw-Hill Book Co.: New York, NY, USA, 1992.
13. Penn, A.; Desyllas, J.; Vaughan, L. The Space of Innovation: Interaction and Communication in the Work Environment. *Environ. Plan. B Plan. Des.* **1999**, *26*, 193–218.
14. Hillier, B.; Iida, S. *Network and Psychological Effects in Urban Movement*; Springer: Berlin/Heidelberg, Germany, 2005.
15. Dalton, R. *Spatial Navigation in Immersive Virtual Environments*; University College London: London, UK, 2001.
16. Helbing, D.; Farkas, I.; Vicsek, T. Simulating dynamical features of escape panic. *Nature* **2000**, *407*, 487–490. [[CrossRef](#)]
17. Klüpfel, H.; Schreckenberg, M.; Meyer-König, T. *Models for Crowd Movement and Egress Simulation*; Springer: Berlin/Heidelberg, Germany, 2005.
18. Wang, D.; Liang, S.; Chen, B.; Wu, C. Investigation on the impacts of natural lighting on occupants' wayfinding behavior during emergency evacuation in underground space. *Energy Build.* **2022**, *255*, 111613. [[CrossRef](#)]
19. Vilar, E.; Rebelo, F.; Noriega, P.; Teles, J.; Mayhorn, C. Signage Versus Environmental Affordances: Is the Explicit Information Strong Enough to Guide Human Behavior During a Wayfinding Task? *Hum. Factors Ergon. Manuf. Serv. Ind.* **2015**, *25*, 439–452. [[CrossRef](#)]
20. Vilar, E.; Rebelo, F.; Noriega, P.; Duarte, E.; Mayhorn, C.B. Effects of competing environmental variables and signage on route-choices in simulated everyday and emergency wayfinding situations. *Ergonomics* **2014**, *57*, 511–524. [[CrossRef](#)] [[PubMed](#)]
21. Snopková, D.; De Cock, L.; Juřík, V.; Kvarda, O.; Tancoš, M.; Herman, L.; Kubíček, P. Isovisits compactness and stairs as predictors of evacuation route choice. *Sci. Rep.* **2023**, *13*, 2970. [[CrossRef](#)] [[PubMed](#)]
22. Güntürkün, O. Adult persistence of head-turning asymmetry. *Nature* **2003**, *421*, 711. [[CrossRef](#)] [[PubMed](#)]
23. Scharine, A.A.; McBeath, M.K. Right-Handers and Americans Favor Turning to the Right. *Hum. Factors J. Hum. Factors Ergon. Soc.* **2002**, *44*, 248–256. [[CrossRef](#)]
24. De Kort, Y.A.; Ijsselstein, W.A.; Kooijman, J.; Schuurmans, Y. Virtual Laboratories: Comparability of Real and Virtual Environments for Environmental Psychology. *Presence* **2003**, *12*, 360–373. [[CrossRef](#)]
25. Kobes, M.; Helsloot, I.; de Vries, B.; Post, J. Exit choice, (pre-)movement time and (pre-)evacuation behaviour in hotel fire evacuation—Behavioural analysis and validation of the use of serious gaming in experimental research. *Procedia Eng.* **2010**, *3*, 37–51. [[CrossRef](#)]
26. Kinatader, M.; Ronchi, E.; Nilsson, D.; Kobes, M.; Müller, M.; Pauli, P.; Mühlberger, A. Virtual reality for fire evacuation research. In Proceedings of the 2014 Federated Conference on Computer Science and Information Systems, Warsaw, Poland, 7–10 September 2014.
27. Kobes, M.; Helsloot, I.; De Vries, B.; Post, J.G.; Oberijé, N.; Groenewegen, K. Way finding during fire evacuation; an analysis of unannounced fire drills in a hotel at night. *Build. Environ.* **2010**, *45*, 537–548. [[CrossRef](#)]
28. Wang, D. *Research on Personnel Fire Evacuation Behavior and Computable Model in Underground Commercial Buildings*; Chongqing University: Chongqing, China, 2021; p. 346.
29. Wang, D.; Zhou, T.; Li, X. Impacts of Environment and Individual Factors on Human Premovement Time in Underground Commercial Buildings in China: A Virtual Reality-Based Study. *ASCE-ASME J. Risk Uncertain. Eng. Syst. Part A Civ. Eng.* **2021**, *7*, 04020056. [[CrossRef](#)]
30. Deng, Q.; Zhang, B.; Zhou, Z.; Deng, H.; Zhou, L.; Zhou, Z.; Jiang, H. Evacuation Time Estimation Model in Large Buildings Based on Individual Characteristics and Real-Time Congestion Situation of Evacuation Exit. *Fire* **2022**, *5*, 204. [[CrossRef](#)]
31. Yang, Y.; Du, H.; Yao, G. A Scientometric Research on Applications and Advances of Fire Safety Evacuation in Buildings. *Fire* **2023**, *6*, 83. [[CrossRef](#)]
32. Dalton, R.C. The Secret Is To Follow Your Nose: Route Path Selection and Angularity. *Environ. Behav.* **2003**, *35*, 107–131. [[CrossRef](#)]
33. Hölscher, C.; Meilinger, T.; Vrachliotis, G.; Brösamle, M.; Knauff, M. Up the down staircase: Wayfinding strategies in multi-level buildings. *J. Environ. Psychol.* **2006**, *26*, 284–299. [[CrossRef](#)]

34. Xie, H.; Filippidis, L.; Galea, E.R.; Blackshields, D.; Lawrence, P.J. Experimental analysis of the effectiveness of emergency signage and its implementation in evacuation simulation. *Fire Mater.* **2012**, *36*, 367–382. [[CrossRef](#)]
35. Tang, C.; Wu, W.; Lin, C. Using virtual reality to determine how emergency signs facilitate way-finding. *Appl. Ergon.* **2009**, *40*, 722–730. [[CrossRef](#)]
36. Nilsson, D.; Frantzich, H.; Wendy, S. Coloured Flashing Lights to Mark Emergency Exits—Experiences from Evacuation Experiments. *Int. Assoc. Fire Saf. Sci.* **2005**, *8*, 569–579. [[CrossRef](#)]
37. Kushner, H.I. Why are there (almost) no left-handers in China? *Endeavour* **2013**, *37*, 71–81. [[CrossRef](#)] [[PubMed](#)]
38. Medland, S.E.; Perelle, I.; De Monte, V.; Ehrman, L. Effects of culture, sex, and age on the distribution of handedness: An evaluation of the sensitivity of three measures of handedness. *Laterality* **2004**, *9*, 287–297. [[CrossRef](#)] [[PubMed](#)]
39. Hofinger, G.; Zinke, R.; Künzer, L. Human Factors in Evacuation Simulation, Planning, and Guidance. *Transp. Res. Procedia* **2014**, *2*, 603–611. [[CrossRef](#)]
40. Fahy, R.; Proulx, G. *Human Behavior in the World Trade Center Evacuation*; Grant/Contract Reports (NISTGCR); National Institute of Standards and Technology: Gaithersburg, MD, USA, 1997.

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